Energy-Delay Analysis of Full Duplex Wireless Communication for Sensor Networks

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***Abstract*—Full duplex wireless communication is a promising new technique that enables the simultaneous transmission and reception of a packet on the same frequency. Until now most research focused on proving the feasibility of full duplex Wi-Fi systems, focusing mainly on PHY layer analysis of the BER or PER. In this paper, the use of full duplex in wireless sensor networks is analysed, and it is shown that this can enable significant energy and delay gains, even when considering a realistic MAC protocol.**

This paper presents a novel full duplex energy model and MAC protocol for wireless sensor networks, compatible with realistic 802.15.4 chips and the standard MAC protocol. We show the potential of full duplex sensor networks, both for networks with low and high loads. Especially for high loads, full duplex enables a promising collision detection, avoiding wasting scarce resources in long packet collisions. Full duplex nodes outperform half duplex nodes both in terms of energy as in terms of delay, even in case of asymmetric traffic conditions. In addition, several advantages exist in terms of fairness of downlink traffic towards uplink traffic.

I. Introduction

Wireless sensor networks (WSNs) are becoming more prevalent in our daily lifes. From smart wristwatches to smart thermostats, everything is connected and measuring our surroundings. From a communications point-of-view, this so called Internet-of-Things has two main challenges, (1) how can we allow all these nodes to send and receive data with a reasonable delay and (2) how to do all this with a minimum of energy. The first challenge is mostly overlooked as the general focus of wireless communication is often throughput or spectral efficiency, measured in bps/Hz at the physical layer (PHY). However, in the coming years delay will become more important, and important PHY innovations need to be evaluated at medium access control (MAC) layer. Delays of 1ms will be needed to enable new applications where tactile feedback is necessary. Applications like exoskeletons for elderly people and self-driving cars which are aware of other cars all need low delay communication, beyond what is currently guaranteed with most communication standards [1]. The second challenge is inversely proportional to the first one, meaning that typically, when a network is optimised for energy, the delay increases. Lowering the energy consumption of sensor nodes is necessary because these nodes should have a lifetime of 10 years, otherwise the cost of replacing the battery becomes too high. We show that both challenges can be tackled by using full duplex wireless communication, i.e., full duplex promises an improved guaranteed uplink/downlink delay at MAC layer without an additional energy penalty.

By using full duplex it is possible to send and receive data in the same time and frequency slot. To do this the self-transmitted signal needs to be removed, ideally the residual self-interference should be below the noise floor. In theory this should be simple because the self-transmitted signal is a known signal and can thus be subtracted from the received signal. In practice however it is more complicated due to non-idealities in the front-end [2]. In most full duplex designs [3], [4], the self-transmitted signal is first cancelled in the analog domain to prevent the analog-to-digital convertor from saturating and then the residual interference is cancelled in the digital domain [2], [3], [4]. Various research groups have shown that it is possible to cancel the self-transmitted signal to enable full duplex. Recently, this has been proven to be feasible using commodity hardware [2], however thus far the focus has always been on achieving a higher throughput in Wi-Fi systems. WSNs rarely use Wi-Fi because of the high power consumption. One of the most used standards for WSNs is the IEEE 802.15.4 standard [5]. The standard defines a low power, low data rate PHY and MAC for personal area networks. In this paper we analyse the effect of using full duplex in WSNs connected in a star topology, and prove that the energy consumption is not increased by doing so, making it a viable candidate for next generation low-delay sensor networks. We modify the 802.15.4 PHY and MAC layers to accommodate for full duplex and run simulations in MATLAB. The most commonly used mode of this MAC is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mode, which we will model here. We will show that even this MAC model, although not designed for low delay, can benefit greatly from the introduction of full duplex. The output of these simulations is then linked with a novel full duplex energy model.

Full duplex can solve one of the biggest problems that make QoS guarantees for wireless communication challenging, i.e., collisions. Collisions occur whenever two or more nodes want to send a packet at the same time, resulting in a superposition of waves at the receiver. Every time a collision takes place, the medium will be busy and other nodes will have to defer their transmissions. The colliding nodes will have to try again after the collision.

Numerous attempts have been made to solve the collision problem, e.g., CSMA/CA which is used in 802.15.4 tries to avoid collisions by randomly backing off, more on this in

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Section II. However CSMA/CA does not work for hidden terminals because the nodes cannot sense each other. Hidden terminals occur when two or more nodes are not in range of each other, whenever they want to send a packet, they can not hear each others transmission and will think the wireless medium is free, resulting in a collision at the receiver. Further, the probability to send successfully using CSMA/CA decreases drastically with the number of nodes, meaning that it doesn't solve the issue for a large number of nodes [6].

Schemes like ZigZag decoding [7] and successive interference cancellation [8] try to recover from the collision by decoding the collision free part of the first packet and subtracting this from the second, now the second packet is partially decoded and so on. These schemes work pretty well for Wi-Fi but are too energy inefficient for sensor networks [9].

Other schemes like collision notification (CSMA/CN) [10] have been proposed to solve both the collision and hidden terminal problem. Here the receiver will send a distinct in-band signature to notify the transmitter of a collision. The transmitter will continuously correlate for this distinct signature and terminate its transmission whenever it receives one. The main disadvantage of the proposed scheme is that additional hardware is needed for the sole purpose of collision notification. To achieve CSMA/CN they need an additional receiver with self-interference cancelation. Moreover, the correlation process is shown to only work up to 36dB of SINR while it has been shown that for 802.11 this ratio can be up to 100dB [3].

Instead of using the additional hardware only for correlation we use a fully working wireless full duplex node. By itself full duplex naturally expands to CSMA with collision detection (CSMA/CD) because whenever a node is transmitting a packet to the sink node, it can use the downlink slot to sense for collisions. However this collision detection only works when both colliding nodes are in range of each other. If they're not, both nodes will not be able to detect each others transmission and the hidden terminal problem occurs.

Our full duplex design enables collision detection while also allowing to solve the hidden terminal problem or increase throughput when uplink/downlink traffic is balanced. The full duplex hardware is thus not only used for collision detection but also allows the sink node to transmit a downlink packet without affecting the network capacity. We will also show that full duplex lowers the energy consumption and allows more nodes to be active in the network.

This paper is constructed as follows, we first briefly explain the IEEE 802.15.4 standard in Section II. Next we will show, in Section III, how WSNs can benefit from full duplex. In section IV we explain the simulation model and in Section V we explain our full duplex energy model and finally we look at our simulation results in Section VI.

II. IEEE 802.15.4 SLOTTED CSMA/CA

In this section we explain the IEEE 802.15.4 slotted CSMA/CA mode. The communication in this mode is build around a superframe which starts with a beacon sent by the sink node. All nodes synchronise to the superframe using this beacon. The superframe is divided in multiple backoff slots, the amount of slots can be adjusted if necessary. The beacon is always sent in the first slot, then the active portion of the superframe follows where nodes can contend for the medium in the contention access period or if they have a slot given to them, they can send in the contention free period and then an inactive portion can follow.

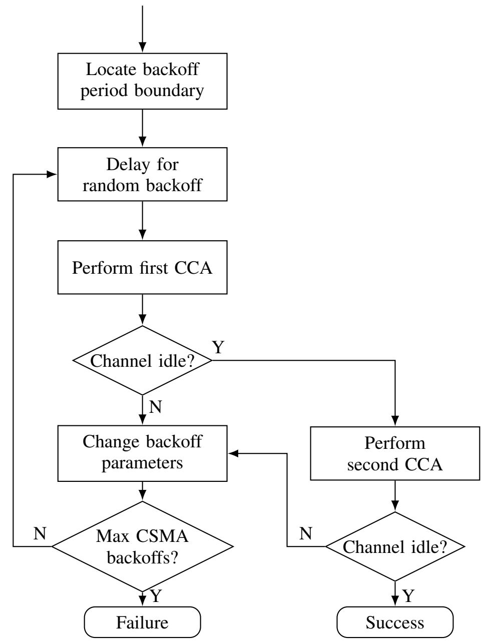

Fig. 1. Slotted CSMA/CA algorithm in 802.15.4

Whenever a node wants to transmit a packet it will need to follow the steps defined in Figure 1. The node will first locate the backoff period boundary to synchronise itself with the superframe slots. Next it will wait for a random time, this random backoff assures that it is unlikely that multiple nodes try to send simultaneously resulting in a collision. Next the nodes perform clear channel assessment (CCA) for two backoff slots. If both times the medium is free they will send their packet. If the channel is not free, the nodes will increase their backoff exponent to backoff even further. If the node has reached its maximum number of backoffs it will report to the upper layers that the transmission has failed.

III. BENEFITS OF FULL DUPLEX FOR WSNS

WSNs can benefit from full duplex in a number of ways, we exploit two. Both changes are fully backwards compatible with current 802.15.4 networks, only the sink node needs to be updated with full duplex capabilities and full duplex nodes need to be added. Furthermore full duplex nodes can coexist with half duplex nodes as the packet and contention structure is basically kept standard compliant.

The first benefit is that a node can transmit and receive at the same time meaning that it can receive a downlink packet from the sink node while transmitting an uplink packet to the sink node. Secondly a full duplex node can use the full duplex downlink slot for collision detection. We will now explain both

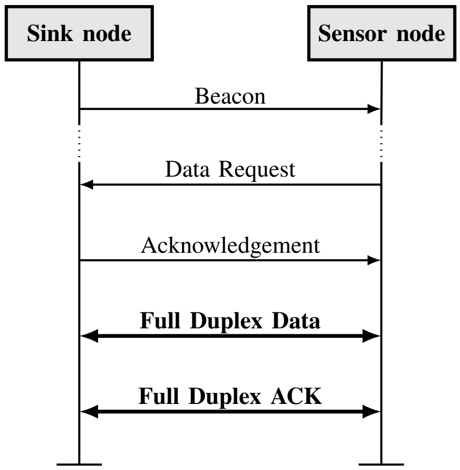

Fig. 2. Message exchanges for full duplex communication

benefits, and show how they can be implemented in enhanced 802.15.4 protocols.

A. Full duplex transmissions

With full duplex communication, sensor nodes have two slots simultaneously available, one for downlink and one for uplink. Figure 2 shows the messages that are exchanged when using full duplex, note that it is very similar to the message exchange for downlink packets. First the sink node will announce in the beacon that it has a packet available for the node. If the node has an uplink packet waiting it will, when it has successfully acquired the medium, send a data request packet to announce a full duplex opportunity. The sink node will acknowledge and then both sensor and sink node will send data in full duplex followed by a full duplex acknowledgment.

The MAC layer will automatically switch to full duplex transmission whenever one of these two scenarios occur:

- the node is contending to receive a downlink packet and an uplink packet arrives;
- the node is contending to send an uplink packet and the sink node announces a downlink packet in the beacon.

In terms of transmission delay, these full duplex transmissions take 1.92ms longer than normal uplink transmissions because of the data request and acknowledgement. Compared to downlink transmissions, there is no difference in transmission delay. For low throughput networks this would mean that full duplex increases the delay, however in low throughput networks most transmissions will be half duplex because both sink node and node will not have a packet ready at the same time. In high throughput networks the delay is mainly dominated by collisions, here full duplex transmissions solve some of the congestion problems if enough full duplex transmissions occur.

B. Full duplex collision detection

With full duplex it is possible to implement a collision detection algorithm, however because of the limited range of the sensor nodes this algorithm only works for non-hidden

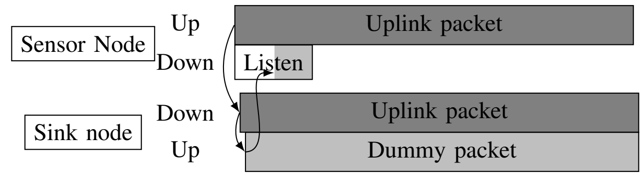

Fig. 3. Full duplex collision detection

nodes. Our solution solves both the collision detection and hidden terminal problem and is shown in Figure 3. To address the hidden terminal problem, the sink node will as soon as it senses a packet, transmit a dummy packet to let all other nodes know that the channel is not idle anymore. If it then discovers there has been a collision, it will stop transmitting this dummy packet. The transmitting nodes will listen on the downlink channel for this dummy packet and will stop transmission as soon as they no longer receive this dummy packet. In a way the dummy packet acts as an instantaneous acknowledgement of the uplink packet or can be used to transfer other control information. The sink node solves the hidden terminal problem by transmitting a dummy packet and the nodes solve the collision detection problem by terminating transmission as soon as they don't receive the dummy packet anymore.

Whenever there is no collision this scheme will introduce some overhead in terms of power consumption because each transmitting node will have to listen the whole time it is transmitting. However in the CSMA/CA protocol (Figure 1) a node needs to sense the channel idle (CCA) for two consecutive timeslots before it can transmit anything. Therefore, because of the dummy packet, it is only possible that a collision occurs in the first timeslot. This collision will occur when the delay between the reception of the uplink packet and the transmission of the dummy packet is larger than the CCA length of the other nodes. The other nodes will then assess the medium free and start transmission in the next timeslot. A collision will thus take place in the next timeslot and the sink node will react to this by stopping the transmission of the dummy packet. This means that it is sufficient that the transmitting node only listens to the dummy packet for two timeslots, after that it can turn off its receiver chain to conserve energy.

As mentioned earlier both additions are fully backwards compatible with existing 802.15.4 nodes, additionally the dummy packet also solves the hidden terminal problem for legacy nodes as well. To accommodate for all this we've added an extra full duplex state to an existing energy model as will be explained in Section V. In the next section we will first explain our simulation model.

IV. Simulation model

To compare our novel full duplex MAC protocol, we have built a simulator which is based on [6]. The pseudocode of our simulator is shown in Algorithm 1. The variables in italic are used for the energy calculations in the next section. Each

TABLE I
POWER CONSUMPTION OF THE DIFFERENT STATES

Shutdown	**Idle**	**RX**	**TX**	**RXTX**
$144nW$	$712\mu W$	$35.28mW$	$30.67mW$	$56.95mW$

iteration of the for loop depicts a backoff slot of the MAC protocol. The simulator keeps also track of the state of the different nodes, to know the current backoff slot's state. These tracking variables are not shown in Algorithm 1.

The simulator first checks if the current slot is a beacon slot, if so we check for downlink traffic and update the necessary variables. If it is not a beacon slot, the simulator checks if the channel is idle and which nodes are ready to transmit. If there is a collision and collision detection is enabled, the number of transmission slots is set to two, as explained in the previous section. Otherwise the nodes will transmit for the full packet length. If there is no collision, the simulator checks the mode of the transmitting node and increments all the necessary variables for the energy calculation. The variable 'packetDelay' is used to calculate the delay, it is the time between the arrival of the packet and the reception of the acknowledgement after the transmission. If the channel is busy, we follow the regular CSMA/CA algorithm. In the end we update the packet arrivals and keep track of the arrival time.

V. ENERGY MODEL

Currently there are no off-the-shelf radios that support full duplex. Therefore we developed an energy model based on a popular 802.15.4 chipset, the TI CC2420 [11]. We start from the energy model from [12], which consists of four state: Shutdown (clock is turned off), Idle (clock is turned on), transmit (TX) and receive (RX) and add a fifth state: full duplex (RXTX) (both receiver and transmitter are active). A node is in the full duplex state whenever it uses collision detection or transmits and receives a packet in full duplex.

A. Full duplex energy

To describe the full energy model of a full duplex wireless transceiver we need the power each state consumes and the transition energy between states. Figure 4 shows the five different states and state transitions. The four basic states are unchanged with respect to [12], only the full duplex 'RXTX' state is added. In this state both the transmitter chain and the receiver chain of the transceiver will be active, because both chains are operating at the same frequency only one Phase Locked Loop (PLL) can be used. From a similar chipset [13] we identified P_{PLL} to be around $9mW$. Table I gives an overview of the power consumption of the different states. The power consumption of the full duplex state is

$$P_{RXTX} = P_{RX} + P_{TX} - P_{PLL}.$$

Next to the different states, Figure 4 also shows the transition energies and times. Again the standard transitions are from [12], the transition from Idle to RXTX is calculated

Algorithm 1 Pseudocode of the simulator

```
initNodes(1:N) = uniformly distributed;
upPacketArrival(1:N) = poisson distributed;
downPacketArrival(1:N) = poisson distributed;
mode(1:N); %uplink, downlink, full duplex
for slot=0:nbSlots do
  if beaconSlot then
    check nodes i for downlink;
    update delay(i), mode(i);
    increment N_B;
  else
    %not a beacon slot
    check idle nodes i;
    increment N_I(i);
    check nodes i performing CCA;
    increment N_CCA(i);
    if channel idle then
      check nodes j from i ready to transmit;
      if enough slots left for transmission then
        if more than one node j then
          %collision
          if collision detection then
            set txSlots(j) = 2;
            increment N_TXcd(j);
          else
            set txSlots(j) = packetLength;
            increment N_TXncd(j);
          end if
        else
          switch (mode(j))
          case uplink:
            increment N_TXcd or N_TXncd;
            increment N_ACKr;
          case downlink:
            increment N_TXcd or N_TXncd;
            increment N_RX, N_ACKt, N_ACKr;
          case full duplex:
            increment N_TXcd, N_ACKr;
            increment N_RXTX, N_ACKrt;
          end switch
          set txSlots(j) = packetLength;
          update packetDelay(j);
        end if
      else
        defer nodes j;
      end if
    else
      %channel is busy
      update nodes i according to CSMA/CA algorithm;
    end if
  end if
  update packet arrivals;
end for
```

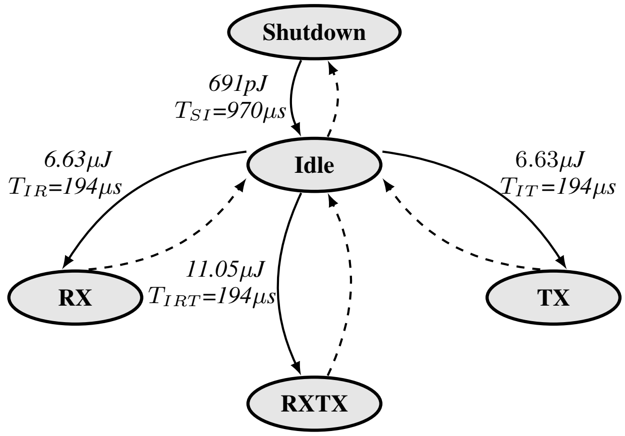

Fig. 4. Transition diagram with transition energies and times

TABLE II
SUBTIMINGS

$\mathbf{T_{CCA}}$	$\mathbf{T_{TXcd}}$	$\mathbf{T_{SI}}$	$\mathbf{T_{IR}}$	$\mathbf{T_{IT}}$	$\mathbf{T_{IRT}}$
128μs	640μs	970μs	194μs	194μs	194μs

using [12]'s rule of thumb ($E = TIV_{DD}$). The transition time is the same as the one for RX and TX because most of the time is lost in locking the PLL. From our MAC model, we can count states and state transitions, to determine energy cost.

B. Average power consumption

The average power consumption of the sensor node is given in Eq. (1), which consists of the sum of all state energies with $s \in \{shutdown, idle, RX, TX, RXTX\}$ and all state transitions with $t \in \{SI, IR, IT, IRT\}$, representing a transition from Shutdown to Idle (SI), from Idle to RX (IR), from Idle to TX (IT) and from Idle to RXTX (IRT), respectively, divided by the total simulation time. The number of slots is equal to the number of simulated timeslots and the length of a timeslot is equal to 0.32ms as defined in the 802.15.4 standard.

$$P_{avg} = \frac{\sum_s P_s T_s + \sum_t P_t T_t}{N_{slot} T_{slot}} \tag{1}$$

We can now link the simulation model with the energy model. We will use variables from Algorithm 1, which counted the number of times a certain action is performed. The subtimings are given in Table II and if not defined they are equal to the slot time (0.32ms).

Several protocol states map to the RX power state, as a node is in receive mode during CCA, packet reception, ACK reception and beacon reception. The total time in the receive state is

$$T_{RX} = \sum_s N_s T_s, \tag{2}$$

with $s \in \{CCA, RX, ACKr, B\}$.

The transmit state is mainly used in half duplex mode without collision detection (ncd), but remember from Section III, a node will only detect collisions during the first two timeslots so for the remaining time he will be in the TX state hence the final term of (3). This gives a total time in the transmit state of

$$T_{TX} = \sum_s N_s T_s + N_{TXcd}(T_{packet} - T_{TXcd}), \tag{3}$$

with $s \in \{TXncd, ACKt\}$.

Similarly, a node is in the full duplex state the first two timeslots when transmitting with collision detection and when he's transmitting a packet or ACK in full duplex. The total time spend in the full duplex state is

$$T_{RXTX} = \sum_s N_s T_s, \tag{4}$$

with $s \in \{TXcd, RXTX, ACKrt\}$.

Nodes are in the idle state when they are backing off and for the remainder of the slot when they perform CCA. This gives a total time of

$$T_{idle} = N_I T_I + N_{CCA}(T_{Slot} - T_{CCA}). \tag{5}$$

Finally, nodes are in the shutdown state when they are not in one of the above states. Next we will discuss the simulation results.

VI. SIMULATION RESULTS

In this section we analyse the delay and energy performance for a range of relevant network configurations. We compare the results of our proposed MAC enhancement with the standard half duplex CSMA/CA protocol. First in Figure 5, we look at the effect of downlink traffic on the uplink throughput, and compare uplink/downlink throughput fairness in our network. We ran simulations with 25 nodes, the total uplink network traffic is fixed at 3 packets/s of 100 bytes. The throughput in the half duplex case starts to decrease starting from 20 kbits/s of downlink traffic, this is mainly due to downlink priotization and collisions. There are not enough collision free slots left for the uplink traffic. In the full duplex case, uplink is not affected by the downlink traffic because they can be transmitted simultaneously, showing the effect of full duplex transmissions.

In most WSNs there will be an asymmetry between up and downlink, therefore in the following results, only 10% of all traffic in the network is downlink. Figure 6 shows the delay results. The nodes in this figure transmit packets with a constant throughput of 3 packets/s of 100 bytes each. Figure 6 shows us that it takes full duplex almost double the amount of active network nodes before the network starts to saturate. The saturation is caused by collisions in the network, and full duplex collision detection has the potential to defer network collapse with 50%. Figure 6 shows another interesting fact, if we compare half duplex and full duplex in non-saturated regions, full duplex is only slightly superior than half duplex in terms of delay.

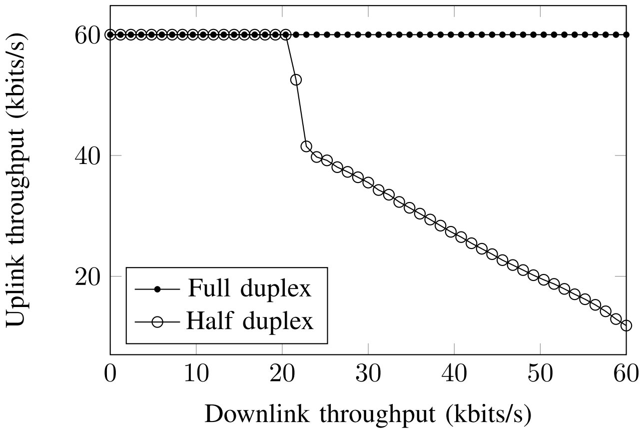

Fig. 5. Effect of downlink traffic on uplink throughput. (25 nodes)

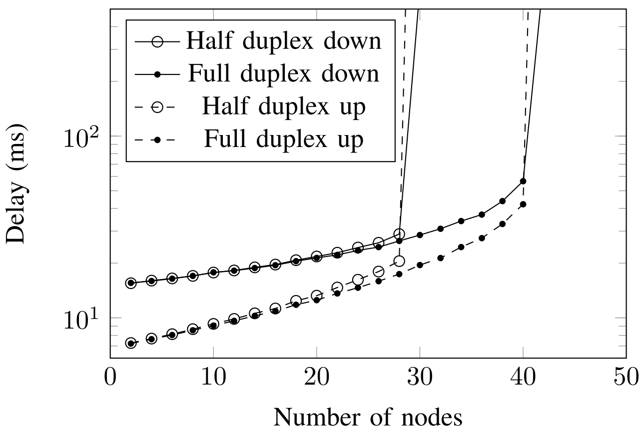

Fig. 6. Delay analysis using a fixed throughput of 3 packets/s with 10% of the packets downlink.

The energy per bit is shown in Figure 7, it uses the same parameters as in the previous figure. Again we see that full duplex starts saturating much later than half duplex. When the network is saturated, the energy consumption with full duplex is lower because of the collision detection. The nodes are less in the high-energy RX or TX states. In the non-saturated region, full duplex performs slightly worse because of the increased energy consumption of the collision detection. In this region, there are not many collisions so collision detection is not necessary here. Overall, we can conclude that the energy penalty is low for full duplex. More importantly, nodes could easily learn when to do full duplex collision detection as function of networking conditions.

VII. Conclusions

In this paper, a novel full duplex MAC protocol and energy model for full duplex wireless sensor networks is presented. The MAC protocol implements a collision detection scheme using an immediate acknowledgement in the form of a dummy packet. We have shown that using full duplex, downlink traffic is almost free and it does not decrease the uplink traffic. We also showed that full duplex only starts to saturate when almost double the nodes as in the half duplex case are active.

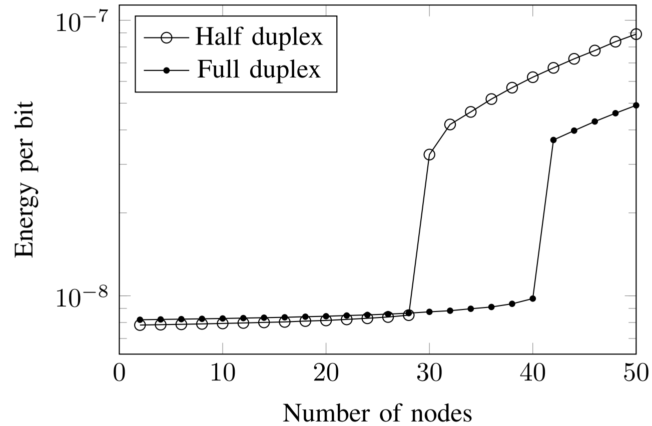

Fig. 7. Energy per bit using a fixed throughput of 3 packets/s with 10% of the packets downlink.

Our novel energy model uses an extra full duplex state. Simulations have shown that whenever the network is saturated, it is better to switch to full duplex. In a non-saturated network, full duplex is only slightly worse.

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